Statistics II
Summary

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First things first: the exam

Exam date & time: **June 21, 10:00–13:00** room: *1314.0026*.

- A mixture of multiple choice and short-anser questions.
- It should take about 90 minutes, but you can use all 3 hours reserved for the exam.
- An example exam is already on Nestor, under 'course documents'.
- You should be able to do without a calculator, but you are allowed to bring a simple calculator (without network capabilities).

The plan of the day

A summary (with a new/different perspective at times):

Basics: hypothesis testing, statistical models.
Correlation
Regression
Multiple regression
ANOVA
Factorial ANOVA
Repeated-measures ANOVA
Logistic Regression

. . . some common problems & your questions.

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- Inferential statistics is about making sense *out* of data.
  - We do not stop with understanding the data, we want generalizations beyond the data at hand.
- Statistics is a collection of tools for converting data into information.

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All of these will be presented to you in some form of statistics.

Null-hypothesis significance testing

- Null-hypothesis significance testing (NHST) is probably most widely used scientific tool.
- It is important to get a fair understanding of it.
- If you are confused, you are not alone. Hypothesis testing is confusing.

Typical NHST procedure

- Define a null hypothesis (H_0) that expresses when your hypothesis is wrong.
- Define an alternative hypothesis (H_a, or H_1) as what you expect to find. (well. . . depending on which NHST procedure you follow.)
- Choose a significance level (α-level) at which to reject the H_0. Typical values are 0.05, 0.01, 0.001.
- Apply the appropriate test, say t-test, which will yield a p-value, of obtaining the sample you have, if H_0 was true.
- If $p < \alpha$, we reject the H_0, otherwise, we fail to reject the H_0.

NHST: problems/suggestions

Beware:

- The p-value is not the probability of null-hypothesis being true.
- Not finding a significant difference does not mean there is none: you can never accept the null hypothesis.
- Statistical significance does not warrant practical importance.

Suggestions:

- Whenever you see a p-value insert ‘if null hypothesis was true’ in your conclusions.
- Report value of the p (not just $p < .05$).
- Always look for effect sizes, interpret along with (confidence) interval estimates around the effect sizes.

Effect sizes: what are they?

A few examples:

- The estimate of the mean.
- The estimate of the difference between two means. Or, *Cohen's d* ($\frac{\bar{x}_1 - \bar{x}_2}{s}$), if you like standardized measures.
- Ratio or percentage of change (say, in a year, or after treatment).
- Correlation coefficient r (or r^2).
- Slope values in a regression analysis.
- Proportion of variance explained by a model: multiple-r^2 (or adjusted-r^2), η^2 (or ω^2).

It is best to interpret effect sizes with respect to the problem studied.

Statistical models

All statistical analyses can be cast into a model:

$$\mathrm{response} = \mathrm{model} + \mathrm{error}$$

- model is what we are interested in.
- error effects the precision (and certainty) of our estimates.
- we prefer models with smaller error.
- we prefer simpler models.

What are the models?

- Model of the mean (sometime called the null model):

$$y = \mu + e$$

- Model with multiple group means (like in ANOVA):

$$y = \mu + \delta_1 + \delta_2 + e$$

- Model with a single predictor (regression, but also t-test):

$$y = a + bx + e$$

- Model with a single predictor (regression, ANOVA):

$$y = a + b_1x_1 + b_2x_2 + \ldots + e$$

Correlation

The correlation coefficient (r) is a standardized symmetric measure of covariance between two variables.

- The correlation coefficient ranges between -1 and 1.
  - -1 perfect negative correlation: x decreases as y increase.
  - 0 no relationship.
  - $+1$ perfect positive correlation: x increases as y increase.
- Correlation is symmetric.
- Typically between two numeric variables, but also with binary categorical variables (point biserial correlation).

Correlation: examples

The relationship between

- Education and income.
- Height and weight.
- Age and ability (e.g., language skills, cognitive functions, eye sight, . . .)
- Speed and accuracy.
- Smoking and life expectancy.
- Time spent for work and success.

Correlation: how to do it

- The most common correlation coefficient is Pearson's r,

$$r_{xy} = \frac{1}{n-1}\sum_{i=1}^{n} z_{x_i} z_{y_i}$$

  r indicates the strength and direction of the correlation.
- Inference can be based on t-distribution, the base on the statistic,

$$t = \frac{r\sqrt{n-2}}{\sqrt{1-r^2}}$$

- Assumptions are exactly like linear regression (coming soon).
- When the assumptions fail, non-parametric alternatives Spearman's ρ or Kendall's τ can be used.

Regression

Regression analysis is about finding the best linear equation that describes the relationship between two variables.

$$y_i = a + bx_i + e_i$$

- y is the *outcome* (or response, or dependent) variable. The index i represent each unit observation/measurement (sometimes called a 'case').
- x is the *predictor* (or explanatory, or independent) variable.
- a is the intercept.
- b is the slope of the regression line.
- $a + bx$ is the *deterministic* part of the model.
- e is the residual, error, or the variation that is not accounted for by the model.

Regression: examples

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The same as correlation, but this time we take a 'sided' perspective.

Regression: how to do it

Least-squares regression is the method of determining regression coefficients that minimizes the sum of squared residuals (SS_R).

$$y_i = \underbrace{a + bx_i}_{\hat{y}_i} + e_i$$

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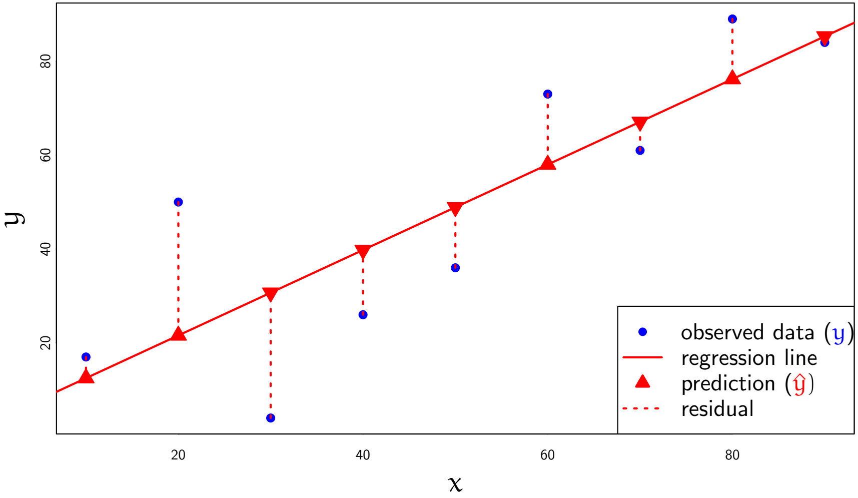
- We try to find a and b, that minimizes the prediction error:

$$\sum_i e_i^2 = \sum_i (y_i - \hat{y}_i)^2 = \sum_i (y_i - (a + bx_i))^2$$

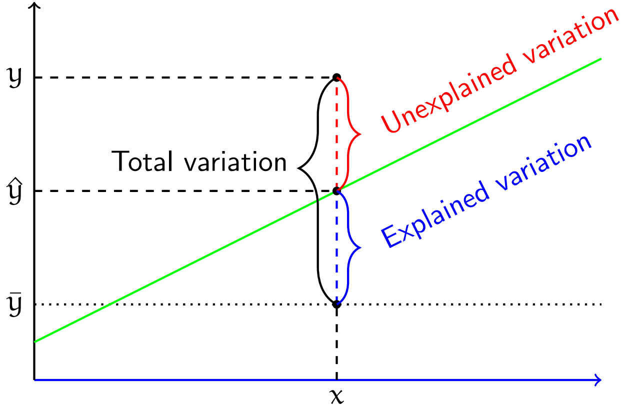
- This minimization problem can be solved analytically, yielding:

$$b = r\frac{\sigma_y}{\sigma_x}$$
$$a = \bar{y} - b\bar{x}$$

Visualization of regression procedure



Variation explained by regression



Total variation	=	Unexplained variation	+	Explained variation
$y - \bar{y}$	=	$y - \hat{y}$	+	$\hat{y} - \bar{y}$

Regression: what to watch out for

- **linearity** scatter plot of 'y vs. x' or 'residuals vs. fitted'.
- **normality** (of residuals!) histogram, Q-Q (or P-P) plot.
- **constant variance** (of residuals!) 'residuals vs. fitted' plot.
- **outliers** scatter plot of 'y vs. x' together with regression line, residual histogram or box plot.
- **influential cases** scatter plot of 'y vs. x', 'residuals vs. fitted', or more specialized statistics like *Cook's distance*.

Regression: when things are not as expected

When things fail . . .

independence	use more complex models (e.g., multilevel/mixed-effect models).
linearity	transform the input or the response variable, use non-linear regression.
normality	transform the input or the response variable, use GLMs with non-normal error.
constant variance	transform the input or the response variable, use GLMs.
influential cases	remove the observation (if it is a real outlier), or collect more data.

Regression: important concepts

- Coefficient of determination

$$r^2 = \frac{\text{Explained variance}}{\text{Total variance}} = \frac{\sum_i^n (\hat{y}_i - \bar{y}_i)^2}{\sum_i^n (y_i - \bar{y}_i)^2} = \frac{SS_M}{SS_T}$$

- r^2 is the standardized effect size for regression. Estimates of slope(s) indicate effect sizes of individual predictors.
- Inference for the complete model is based on F distribution with $DF = (k, n - k - 1)$

$$F = \frac{\text{Explained variance}}{\text{Unexplained variance}} = \frac{\frac{1}{k}\sum_i^n (\hat{y}_i - \bar{y}_i)^2}{\frac{1}{n-k-1}\sum_i^n (y_i - \hat{y}_i)^2} = \frac{MS_M}{MS_R}$$

  for n data points and k predictors.
- Inference (confidence intervals or significance testing) for individual coefficients are performed using t-test.

Multiple regression

$$y_i = \underbrace{a + b_1 x_{i,1} + b_2 x_{2,i} + \ldots + b_k x_{k,i}}_{\hat{y}} + e_i$$

a is the intercept (as before).

$b_{1..k}$ are the coefficients of the respective predictors.

e is the error term (residual).

It is a generalization of simple regression with some additional power and complexity.

Multiple regression: examples

- university performance dependent on general intelligence, high school grades, education of parents,...
- income dependent on years of schooling, school performance, general intelligence, income of parents,...
- level of language ability of immigrants depending on
  - leisure contact with natives
  - age at immigration
  - employment-related contact with natives
  - professional qualification
  - duration of stay
  - accommodation

Multiple regression: issues and difficulties

Multiple regression shares all aspects/assumptions of simple regression, and

- Visual inspection of the data becomes more difficult.
- Multicollinearity causes problems in estimation and interpretation of multiple-regression models.
- Suppression is another possibility, where combination of predictors are more useful than individual predictors.
- Overfitting, occurs when there are large number of predictors.
- Model selection (finding a model that fits the
- Model fit is still measured by r^2 (but, called multiple-r^2). Adjusted-r^2 corrects by-chance increase in multiple-r^2 by adding more predictors.

ANOVA

We want to know whether there are **any** differences between the means of k groups.

- If the variance between the groups is higher than the variance within the groups, there must be a significant group effect.
- Between group variance ($MS_{between}$, or MS_M or MS_G) is characterized by variance between the group means.
- Within group variance (MS_{within}, or MS_R or MS_E) is characterized by variance of data round the group means.

Then, the statistic of interest is

$$F = \frac{MS_{between}}{MS_{within}} = \frac{MS_M}{MS_R}$$

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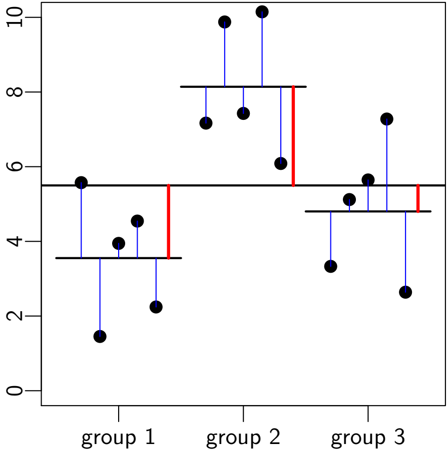
What is the 'model' here?

ANOVA: visualization



$$F = \frac{MS_M}{MS_R}$$

$$F = \frac{\frac{SS_M}{DF_M}}{\frac{SS_R}{DF_R}}$$

$$DF_M = k - 1$$
$$DF_R = n - k$$

where k is the number of groups, and n is the number of observations.

ANOVA: examples

- Compare time needed for lexical recognition in
  1. healthy adults
  2. patients with Wernicke's aphasia
  3. patients with Broca's aphasia
- Effect of background color choice in a web site.
- Compare Dutch proficiency scores of second language learners based on their native language.

ANOVA: what to watch out for

normality of response in all groups check with,

- box plots,
- histogram,
- Q-Q (or P-P) plot.

homogeniety of variance among the groups.

- Rule of thumb: no variance twice another group's variance.
- Box plots for visual inspection.
- Formal tests include 'Levene' or 'Bartlett' tests of homogeneity of variances.

ANOVA: when things go wrong

independence
: Use repeated-measures ANOVA, or multilevel/mixed-effect linear models.

normality
: Transform the response variable, or use non-parametric Kruskal–Wallis test or more complex (linear) models.

homogeniety of variance
: Use corrected F-ratios, transform the response variable.

Prior contrasts and post-hoc tests

- ANOVA indicates whether there are **any** differences between any pair of group means.
- A limited set of specific differences (contrasts) can be coded in ANOVA analysis.
- One can also do post-hoc tests for comparing individual group means after ANOVA analysis.
- In exploratory multiple-comparison analysis, you need to adjust your p-values (or your α level), for example using Bonferroni correction.

Factorial ANOVA

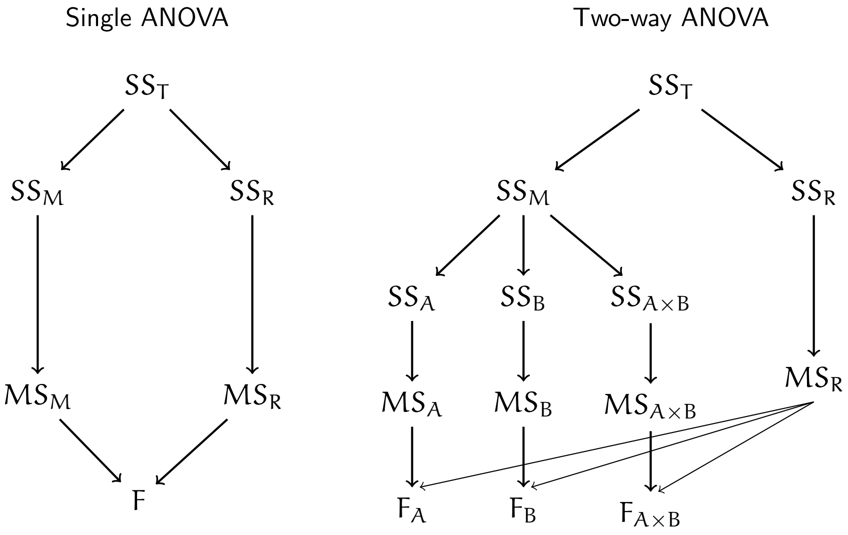
- Factorial ANOVA is a generalization of single ANOVA (or t-test).
- Compare groups along more than one dimension.
- Efficient in use of subjects.
- Allows to investigate interaction.
- Same assumptions with single ANOVA.
  - independent observations.
  - all groups are (approximately) normally distributed
  - all groups have (approximately) equal variances

Factorial ANOVA: examples

- Compare time needed for lexical recognition in
  1. healthy adults
  2. patients with Wernicke's aphasia
  3. patients with Broca's aphasia

  and gender of the subject.
- Usability of an application based on different user interfaces and input methods.
- Language development of children based on their parent's education and socio-economic status.
- Compare Dutch proficiency scores of second language learners based on their native language and profession.

Factorial ANOVA: partitioning the variance



ANOVA: main effects and the interaction(s)

- For two-way ANOVA, with factors A and B, SS_M is partitioned as:

$$SS_M = \underbrace{SS_A + SS_B}_{\text{main effects}} + \underbrace{SS_{A\times B}}_{\text{interaction}}$$

- For three-way ANOVA, with factors A, B and C, SS_M is partitioned as:

$$SS_M = \underbrace{SS_A + SS_B + SS_C}_{\text{main effects}} + \underbrace{SS_{A\times B} + SS_{A\times C} + SS_{B\times C}}_{\text{2-way interctions}} + \underbrace{SS_{A\times B\times C}}_{\text{3-way inter.}}$$

Factorial ANOVA: degrees of freedom and F-tests

As in single ANOVA:

$$\begin{aligned} DF_T &= DF_M + DF_R \\ n-1 &= k-1 + n-k \end{aligned}$$

If we have k_A levels due to factor A, and k_B levels due to factor B, total number of groups is $k = k_A \times k_B$. We can now further partition the DF_M as,

$$\begin{aligned} DF_M &= DF_A + DF_B + DF_{A\times B} \\ k-1 &= k_A - 1 + k_B - 1 + (k_A - 1) \times (k_B - 1) \end{aligned}$$

For two-way ANOVA we get three F-tests:

$$\begin{aligned} F_A &= \frac{MS_A}{MS_R} \\ F_B &= \frac{MS_B}{MS_R} \\ F_{A\times B} &= \frac{MS_{A\times B}}{MS_R} \end{aligned}$$

Repeated-measures ANOVA

Essentially, (factorial) ANOVA, with repeated (not independent) measurements.

- A lot more economical in experiment design.
- More powerful, since individual variation is not a problem for RM ANOVA.
- A generalization of paired t-test to multiple groups.

Repeated measures can be,

over time: testing effects of treatment, teaching method or just time. Typically you get more than two pre-tests or post-tests.

not time related. Examples:

- reaction time for different sort of stimuli
- measurements taken in the same city/region/country

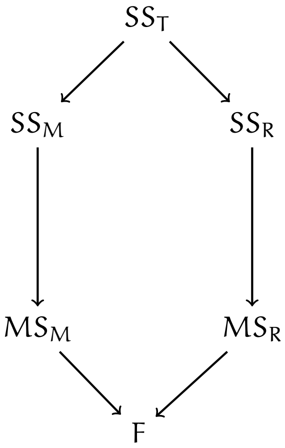
RM ANOVA: Between subjects and within subjects variance

- A between subjects variance is the variation you observe due to differences between individuals.
- In independent (single or factorial) ANOVA, all variation observed is between subjects.
- A within subjects variation is due to variation observed in repeated measurement over the same subject.
- In a purely repeated design ANOVA, all experimental effect is confined in within-subjects variance.

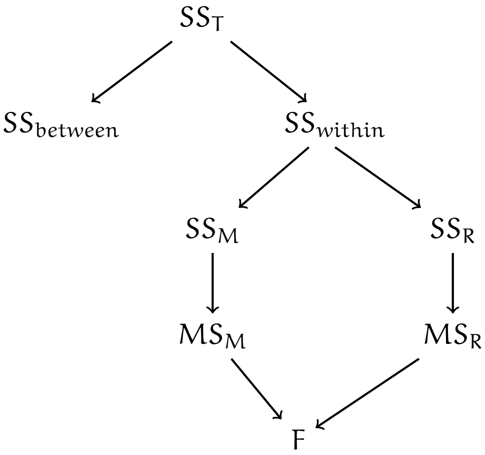
Note: measures do not have to be repeated over ‘subjects’, can be other ‘items’ present in the experimental setup.

RM ANOVA: Partitioning the variance

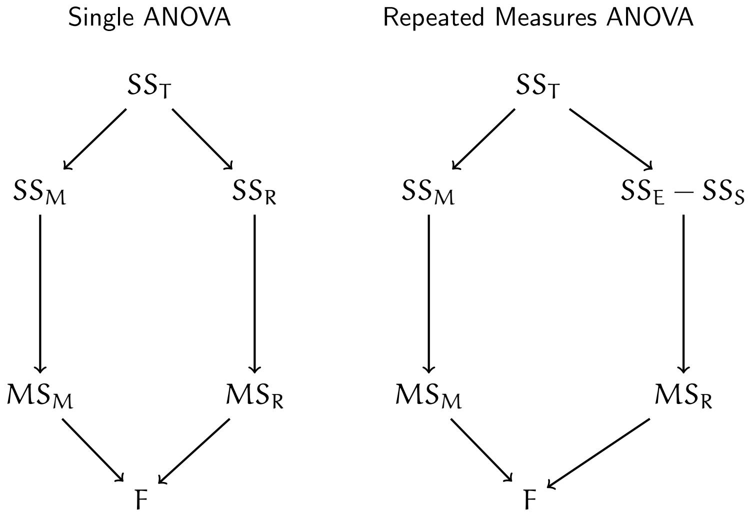
Single ANOVA



Repeated Measures ANOVA



RM ANOVA: partitioning the variance (2)



RM ANOVA: what to watch out for

- Assumptions
  - Normality of response variable in all experimental conditions.
  - Sphericity: homogeneity of variances of all pairwise differences.
- RM ANOVA is very sensitive to unbalanced designs, missing values.
- Carry-over effects (e.g., learning or fatigue) in experiment sequence.

RM ANOVA: when things fail

normality
: transformation or more complex models (generalized linear multilevel/mixed-effect models) may help.

sphericity
: use adjusted F-values or again complex models (generalized linear multilevel/mixed-effect models) may help.

unbalanced data
: generalized linear multilevel/mixed-effect models, or recollect your data more carefully.

carryover effects
: randomize the order of stimuli during the experiment, or switch to between-subjects designs, do multiple experiments.

ANOVA and effect size

- ANOVA as a model view:
  - η^2 ($= r^2$, same calculation, same interpretation, just different name).

$$\eta^2 = \frac{\text{Explained variance}}{\text{Total variance}} = \frac{SS_M}{SS_T}$$

  - partial-η^2 in factorial ANOVA gives variance explained by each factor (or interaction term).
  - Analogous to adjusted-r^2, ω^2 is adjusts for by-chance increase in η^2. Use/report (partial-)ω^2 when you can.
- ANOVA as hypothesis testing method:
  - Mean differences (or Choen's d) in pairwise comparisons.
  - Coefficients of contrasts.

Logistic regression

Logistic regression is an extension of regression (or a case of generalized linear models) where response variable is binary.
Two important differences:

- Transform the response variable so that estimated values are between 0 and 1.
- Allow non-normal residuals.

$$\underbrace{\mathrm{logit}(p_i)}_{\log\frac{p}{1-p}} = a + b_1 x_{1,i} + \ldots + b_k x_{k,i} + e_i$$

Logistic regression: examples

- survival after a surgery depending on age, length of surgery, . . .
- whether purchase occurs depending on age, income, website characteristics, . . .
- whether speech errors occur depending on alcohol level
- when linguistic rules apply (final [t] in Dutch) depending on speed of utterance, stress, social group, . . .
- whether one votes to a political party (or not) depending on age, income, ethnicity, . . .

Logistic regression: estimation

- Maximum likelihood estimation (MLE) tries to find the set of model parameters, or coefficients, a, b_1, $\ldots b_k$, which make the data most likely (or minimize the error).
- MLE is an iterative search for the optimum parameter values. There is no exact solution.
- In some cases, MLE may fail to find a solution.
- If errors are normally distributed, MLE is equivalent to least-squares estimation.
- With MLE, r^2 is not the measure of model fit. Instead we use $deviance = -2LogLikelihood$ to measure model fit (lower, better).
- Unlike r^2, deviance is not comparable for models fit on different data.

Logistic regression: what to watch out for

- Binomial response = non-normal errors.
- Overdispersion: when variance diverges from what is expected in binomial data.
- Linear relationship between logit transformed response and predictors.
- MLE related: MLE may fail to find a good fit. In case of
  - complete separation.
  - unevenly distributed data points.
- Otherwise the same as multiple regression.

Logistic regression: when things fail

overdispersion GLMs with quasi-binomial error.

MLE fails Collect more data, or use Bayesian estimation.

independence Same as regression: multilevel (generalized) linear models.

linearity Same as regression: transform predictor/response or use non-linear regression.

Least-squares estimation

Quiz 1, Question 9 (6.7 average).

Least-squares regression equation is determined by minimizing the square of the

A. differences between observed y values and predicted y values.

B. differences between observed x values and predicted x values.

C. distance between the regression line and the observed data point.

D. correlation coefficient.

Correlation and variance explained

Quiz 1, Question 4 (6.5 average).

A researcher finds a correlation of r=0.4 between IQ and creativity scores. What percentage of the variance in creativity scores is **not** explained by the IQ?

A. 40%

B. 60%

C. 84%

D. 16%

r^2 from sums of squares

Quiz 2, Question 9 (3.5 average).

For a linear regression model, total variance of the response variable, $SS_T = 2500$ and residual sum of squares, $SS_R = 500$. Find the multiple-r^2.

F-ratio from sums of squares

Quiz 3, Question 4 (3.0 average).

In an ANOVA with six groups and 10 participants in each group, between group sum of squares, $SS_M = 55$ and within group sum of squares, $SS_R = 108$. What is the F value?

Interaction terms in a 4-way ANOVA

Quiz 4, Question 7 (1.4 average).

What is the number of interaction terms in a 4-way ANOVA?

RM ANOVA number of subjects

Quiz 5, Question 3 (0.8 average).

A researcher reports a repeated-measures ANOVA F-value with df = 2,40. How many subjects participated in the experiment?